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Footwear Science, 2015
Vol. 0, No. 0, 1–8, http://dx.doi.org/10.1080/19424280.2015.1084389

The effects of shoe temperature on the kinetics and kinematics of running

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(*Received 17 May 2015; accepted 14 August 2015*)

The aim of the current investigation was to examine the effects of cooled footwear on the kinetics and kinematics of running in comparison to footwear at normal temperature. Twelve participants ran at 4.0 m/s ± 5% in both cooled and normal temperature footwear conditions over a force platform. Two identical footwear were worn, one of which was cooled for 30 min. Lower extremity kinematics were obtained using a motion capture system and tibial accelerations were measured using a triaxial accelerometer. Differences between cooled and normal footwear temperatures were contrasted using paired samples *t*-tests. The results showed that midsole temperature (cooled = 4.21 °C and normal = 23.25 °C) and maximal midsole deformation during stance (cooled = 12.85 mm and normal = 14.52 mm) were significantly reduced in the cooled footwear. In addition, instantaneous loading rate (cooled = 186.21 B.W/s and normal = 167.08 B W/s), peak tibial acceleration (cooled = 12.75 g and normal = 10.70 g) and tibial acceleration slope (cooled = 478.69 g/s and normal = 327.48 g/s) were significantly greater in the cooled footwear. Finally, peak eversion (cooled = −10.57 ° and normal = −7.83°) and tibial internal rotation (cooled = 10.67 ° and normal = 7.77°) were also shown to be significantly larger in the cooled footwear condition. This study indicates that running in cooled footwear may place runners at increased risk from the biomechanical parameters linked to the aetiology of injuries.

Keywords: footwear; biomechanics; midsole; temperature; running

Introduction

Recreational distance running has been shown to be physiologically beneficial (Lee et al., 2014). However, aetiological research investigating the prevalence of running pathologies indicates that chronic injuries are a frequent complaint for both recreational and competitive runners (Taunton et al., 2002). Over the course of one year, as many as 80 % of runners will suffer from a chronic musculoskeletal injury as a consequence of their running training (Van Gent et al., 2007).

During the impact phase running, the rapid deceleration of the stance limb causes a transient force to be transmitted through the musculoskeletal system (Whittle, 1999). The repetitive transmission of these forces is linked to the aetiology of some overuse injuries in runners (Whittle, 1999). As the primary interface between the runner and the surface during locomotion, the running shoe has been advocated as a key mechanism by which chronic injuries may be mediated (Shorten, 2000). The properties of the shoe midsole have, therefore, been cited as being particularly important, as they have the potential to influence the impact forces linked to the aetiology overuse injuries.

The most frequently utilised material for running shoe midsoles is a copolymer called ethylene-vinyl acetate. Like most polymers ethylene-vinyl acetate exhibits viscoelastic properties (Knauss, Emri, & Lu, 2008). It has long been established that the mechanical properties of most polymers are highly temperature dependent (Dib et al., 2005); at lower temperatures the materials become less deformable whereas the opposite occurs at higher temperatures. As such, it has been proposed that the cushioning characteristics of running shoes may differ in different environmental temperature conditions.

The effects of different shoe midsole temperatures have been investigated previously in biomechanical literature. Kinoshita and Bates (1996) examined the effects of different environmental temperature conditions on the mechanical properties of running shoe midsoles using impact testing. With increasing temperature, peak acceleration and energy absorption decreased, and the times to peak acceleration and peak deformation increased. Shariatmadari, English, and Rothwell (2010) used finite element modelling to investigate the effect of different footwear temperatures (10, 15, 20, 25, 30, 35, 40 °C) on foot plantar stress. They showed that temperature

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variation significantly affected the mechanical properties of the shoe midsole. Specifically, low temperatures were associated with increased stress due to a stiffening of the midsole, whereas higher temperatures were also linked to high stress due to a bottoming-out effect of the midsole itself. Finally, Shariatmadari et al. (2011) examined eight different shoe midsoles. Each midsole was subjected separately to quasi-static compression and shear force loading under varying temperature conditions (−10, 0, 10, 15, 20, 25, 30, 40 °C). Their findings showed that all eight midsoles were significantly affected by temperature. Specifically, all of the midsoles exhibited softening with increasing temperature whilst lower temperatures led to greater energy absorption capability for a specific value of strain due to increasing stiffness.

However, the effects of footwear temperature on the mechanics of running have not been investigated using human participants. The aim of the current investigation was, therefore, to examine the effects of cooled footwear on the kinetics and kinematics of running in comparison to footwear at normal temperature. This study tests the hypothesis that cooled footwear will be associated with increased impact loading compared to those at normal temperature.

Methods

Participants

Twelve recreational university level female runners took part in the current investigation. All were free from musculoskeletal pathology at the time of data collection and provided written informed consent. Age = 21.45 ± 2.98 years, height = 1.66 ± 0.06 m, mass = 60.87 ± 4.37 kg. The procedure utilised for this investigation was approved by the University of Central Lancashire, ethical committee.

Procedure

Footwear temperature

The footwear used during this study consisted of a Nike Free run 5.0 + trainer in shoe sizes 5−7 UK. Two identical trainers in each size were used, one of which was chilled (cooled) and one was maintained at room temperature (normal). To cool the experimental footwear, they were placed inside a freezer which maintained a constant temperature of −25 °C for 30 min. The midsole temperature in was quantified in both cooled and normal conditions using a digital thermometer. In accordance with the guidelines of Kinoshita and Bates (1996), the midsole temperature was measured at the heel of the right trainer via a small hole drilled from the medial aspect of the shoe midsole. To ensure consistency of midsole temperature, the measurement location was taken 40 mm from the extreme rear of the heel, 35 mm from the medial aspect, and 18 mm above the outsole. Following quantification of footwear temperature, the cooled footwear were immediately worn by participants for data collection. Midsole temperature was recorded before and after running data collection. The temperature of the biomechanics laboratory was 21.12 ± 1.15 °C. The order in which participants ran in the cooled and normal temperature footwear was randomised.

Experimental set-up

Participants completed five trials running in a 22 m biomechanics laboratory at 4.0 m/s in both cooled and normal footwear. The participants struck an embedded piezoelectric force platform (Kistler Instruments, Model 9281CA) sampling at 1000 Hz with their right foot (Sinclair, Hobbs, Taylor, Currigan, & Greenhalgh, 2014). The running velocity was monitored using infrared timing gates (SmartSpeed Ltd, UK) which were positioned 4 m apart and either side of the force platform. The stance phase of the running cycle was delineated as the time over which >20 N vertical force was applied to the force platform (Sinclair, Edmundson, Brooks, & Hobbs, 2011). Kinematic information was collected using an eight-camera optoelectric motion capture system. Synchronised kinematic and ground reaction force data were obtained using Qualisys track manager software (Qualisys Medical AB, Goteburg, Sweden) with a capture frequency of 250 Hz.

The calibrated anatomical systems technique was utilised to model the body segments in six degrees of freedom (Cappozzo et al., 1995). To define the segment co-ordinate axes of the right foot, shank and thigh, retroreflective markers were placed unilaterally onto the calcaneus, the first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral epicondyle of the femur and greater trochanter. To define the pelvic segment, additional markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. The hip joint centre was determined using regression equations based on the ASIS markers (Sinclair, Taylor, Currigan, & Hobbs, 2014). Carbon fibre tracking clusters were attached to the shank and thigh segments. The foot was tracked using the calcaneus, the first and fifth metatarsal markers, and the pelvis was tracked using the ASIS and PSIS markers. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right-hand rule and was oriented from medial to lateral. To measure midsole compression, a smaller

Figure 1. Experimental footwear fitted with 10-mm marker.

10-mm marker was positioned on the top of the shoe midsole at the rear of the shoe (Figure 1).

In addition, a triaxial (Biometrics ACL 300, Gwent, United Kingdom) accelerometer sampling at 1000 Hz was utilised to measure axial accelerations at the tibia. The device was mounted on a piece of lightweight carbon fibre material using the protocol outlined by Sinclair, Greenhalgh, Brooks, Edmundson, and Hobbs (2013). The combined mass of the accelerometer and mounting instrument was 9 g. The device was attached securely to the distal anterio-medial aspect of the tibia in alignment with its longitudinal axis 8 cm above the medial malleolus. This location was selected to attenuate the influence ankle rotation can have on the acceleration magnitude (Lafortune & Hennig, 1991). Strong non-stretch adhesive tape was placed over the device and leg to avoid overestimating the acceleration due to tissue artefact.

Data processing

Retroreflective markers were digitised using Qualisys Track Manager in order to identify appropriate markers then exported as C3D files. Three-dimensional (3-D) kinematics were quantified using Visual 3-D (C-Motion Inc, Germantown, MD, USA) after marker displacement data were smoothed using a low-pass Butterworth fourth-order zero-lag filter at a cut-off frequency of 12 Hz. 3-D kinematics were calculated using an *XYZ* sequence of rotations. All kinematic waveforms were normalised to 100% of the stance phase, and then processed trials were averaged. Discrete 3-D kinematic measures from the ankle and tibia which were extracted for statistical analysis were (1) angle at footstrike, (2) angle at toe-off, (3) range of motion from footstrike to toe-off during stance, (4) peak angle, (5) relative range of motion (representing the angular displacement from footstrike to peak angle), (6) ratio of eversion relative range of motion/relative tibial internal rotation range of motion (EV/TIR ratio), (7) midsole deformation (representing the maximum change in vertical position of the 10-mm marker during the first 25 % of the stance phase). Tibial internal rotation was quantified as a function of tibial co-ordinate system in relation to the foot co-ordinate axes, in accordance with previous work (Eslami et al., 2007).

Forces were reported in body weights (B.W) to allow normalisation of the data among participants. From the force plate data average loading rate, instantaneous loading rate, peak impact force and time to peak impact were calculated. The average loading rate was calculated by dividing the impact peak magnitude by the time to the impact peak. The instantaneous loading rate was quantified as the maximum increase in vertical force between adjacent data points.

The tibial acceleration signal was filtered using a 60-Hz Butterworth zero-lag fourth-order low-pass filter to prevent any resonance effects on the acceleration signal. Peak tibial acceleration was defined as the highest positive acceleration peak measured during the stance phase. The tibial acceleration slope was quantified by dividing the peak tibial acceleration by the time taken from footstrike to peak tibial acceleration.

Statistical analysis

Descriptive statistics (means and standard deviations) were obtained for each footwear temperature. Differences in footwear temperature, midsole deformation, kinetics and 3-D kinematic parameters between cooled and normal footwear conditions were examined using paired samples *t*-tests, with statistical significance accepted at the

$p < 0.05$ level in accordance with the recommendations of Sinclair, Taylor, and Hobbs (2013a). All statistical tests were conducted using SPSS v22.0 (SPSS Inc, Chicago, IL, USA).

Results

Footwear temperature and midsole deformation

Immediately prior to data collection, the temperature of the normal footwear was 23.25 ± 1.21 °C, whereas the cooled footwear was 4.21 ± 0.74 °C. Immediately following data collection, the normal footwear has a temperature of 26.52 ± 1.43 °C and the cooled footwear has a temperature of 7.73 ± 1.19 °C. In both instances, the temperature of the cooled footwear was significantly ($p < 0.05$) lower than the normal shoes. The average duration for data collection in each footwear was 5.89 ± 1.47 min. Finally, the analysis of midsole deformation showed that the cooled footwear (12.85 ± 5.01 mm) were associated with a significantly ($t_{(11)} = 3.04$, $p < 0.05$) reduced deformation in comparison to the normal temperature condition (14.52 ± 4.56 mm).

Kinetics

The cooled footwear were associated with a significantly ($t_{(11)} = 3.95$, $p < 0.05$) increased peak tibial acceleration. In addition, the time to peak tibial acceleration was significantly ($t_{(11)} = 2.77$, $p < 0.05$) shorter in the cooled condition. Tibial acceleration slope was shown to be significantly ($t_{(11)} = 4.10$, $p < 0.05$) greater in the cooled footwear. Finally, it was also demonstrated that the instantaneous loading rate was also significantly larger ($t_{(11)} = 2.65$, $p < 0.05$) in the cooled footwear condition (Table 1).

Kinematics

Hip

No significant ($p > 0.05$) differences in hip joint kinematics were found.

Table 1. Loading rate and tibial acceleration parameters as a function of footwear temperature.

	Normal		Cooled		
	Mean	SD	Mean	SD	
Peak tibial acceleration (g)	10.70	2.31	12.75	4.62	*
Time to tibial acceleration (ms)	33.25	11.89	26.61	10.53	*
Tibial acceleration slope (g/s)	327.48	167.89	478.69	175.80	*
Instantaneous loading rate (B.W/s)	167.08	58.30	186.21	54.17	*

Notes: * = significant difference.

Table 2. Hip kinematic parameters as a function of footwear temperature.

	Normal		Cooled	
	Mean	SD	Mean	SD
Sagittal plane				
Angle at footstrike (°)	43.97	12.27	45.12	9.96
Angle at toe-off (°)	0.17	9.18	0.70	7.84
Peak flexion (°)	44.75	12.08	45.86	9.97
Range of motion (°)	43.79	4.81	44.42	4.20
Relative range of motion (°)	0.78	1.07	0.74	1.38
Coronal plane				
Angle at footstrike (°)	4.25	5.87	3.47	7.19
Angle at toe-off (°)	−1.76	4.16	−2.83	5.31
Peak adduction (°)	9.90	5.96	9.23	6.99
Range of motion (°)	6.27	3.12	6.54	3.79
Relative range of motion (°)	5.66	3.66	5.76	3.33
Transverse plane				
Angle at footstrike (°)	−1.73	12.88	0.76	11.00
Angle at toe-off (°)	−7.28	10.98	−5.18	8.28
Peak external rotation (°)	−10.93	12.51	−9.22	8.65
Range of motion (°)	7.06	5.94	7.22	6.37
Relative range of motion (°)	9.19	5.92	9.98	6.84

Table 3. Knee kinematic parameters as a function of footwear temperature.

	Normal		Cooled	
	Mean	SD	Mean	SD
Sagittal plane				
Angle at footstrike (°)	20.15	8.91	20.58	7.69
Angle at toe-off (°)	16.87	6.64	18.14	4.55
Peak flexion (°)	45.04	6.29	46.30	4.83
Range of motion (°)	6.66	4.26	6.42	4.92
Relative range of motion (°)	24.88	5.33	25.72	6.03
Coronal plane				
Angle at footstrike (°)	−3.99	4.31	−2.48	4.94
Angle at toe-off (°)	−4.55	3.20	−2.87	2.59
Peak abduction (°)	−10.50	5.29	−8.96	4.30
Range of motion (°)	2.43	2.65	2.62	2.61
Relative range of motion (°)	6.50	5.10	6.48	5.12
Transverse plane				
Angle at footstrike (°)	−1.04	8.82	−2.33	7.57
Angle at toe-off (°)	−5.57	7.78	−6.84	6.98
Peak internal rotation (°)	10.95	6.07	10.85	6.45
Range of motion (°)	6.47	2.58	6.00	3.60
Relative range of motion (°)	11.97	5.68	13.18	6.27

Table 4. Ankle kinematic parameters as a function of footwear temperature.

	Normal		Cooled		
	Mean	SD	Mean	SD	
Sagittal plane					
Angle at footstrike (°)	2.83	9.99	3.28	9.29	
Angle at toe-off (°)	−24.63	6.93	−24.12	6.02	
Peak dorsiflexion (°)	18.06	3.56	18.00	3.20	
Range of motion (°)	27.46	8.14	27.40	7.14	
Relative range of motion (°)	15.24	8.12	14.73	7.44	
Coronal plane					
Angle at footstrike (°)	6.28	1.97	4.82	3.30	
Angle at toe-off (°)	4.22	4.69	2.66	4.08	
Peak eversion (°)	−7.83	4.78	−10.57	5.58	*
Range of motion (°)	4.22	3.09	4.54	2.91	
Relative range of motion (°)	14.11	5.40	15.39	6.26	
Transverse plane					
Angle at footstrike (°)	1.23	4.57	0.84	3.55	
Angle at toe-off (°)	6.33	4.11	5.95	4.08	
Peak rotation (°)	−0.19	3.28	0.92	4.17	
Range of motion (°)	5.55	2.75	5.35	2.85	
Relative range of motion (°)	4.57	3.15	3.82	2.70	

Notes: * = significant difference.

Knee

No significant ($p > 0.05$) differences in knee joint kinematics were found.

Ankle

The cooled footwear were associated with a significantly ($t_{(11)} = 3.95$, $p < 0.05$) increased peak eversion (Table 4; Figure 2).

Tibia

The cooled footwear were associated with a significantly ($t_{(11)} = 4.22$, $p < 0.05$) increased tibial internal rotation (Table 5; Figure 3).

Discussion

The aim of the current investigation was to examine the effects of cooled footwear on the kinetics and kinematics of running in comparison to footwear at normal temperature. To authors' knowledge this represents the first examination to investigate the effects of footwear temperature on the mechanics of running *in vivo*.

The first key observation from this work is that the cooled footwear were associated with a significant increase in instantaneous loading rate, tibial acceleration slope and peak tibial acceleration. This supports our hypothesis and agrees with those of Kinoshita and Bates (1996). In addition, this finding may have clinical significance as excessive impact loading has been implicated in the aetiology of chronic running injuries (Milner et al., 2006; Whittle, 1999). This observation, therefore, suggests that running in cooled footwear may increase the risk of overuse injury occurrence; although potentially only in the initial aspect of a run given that the midsole temperature rises as the duration of running increases (Kinoshita & Bates, 1996).

It is hypothesised that this observation relates to the decreased temperature of the cooled footwear midsole. Ethylene-vinyl acetate exhibits viscoelastic properties, as such at lower temperatures the material becomes less deformable (Dib et al., 2005). It can be concluded that this reduction in temperature was responsible for the subsequent reduction in midsole deformation shown in the cooled condition. Impact loading is determined by the rate at which the momentum of the foot changes (Whittle, 1999); therefore, a reduced midsole deformation would serve to increase the impact magnitude.

The second key observation from this study is that significant increases in peak eversion and tibial internal rotation were found in the cooled condition. It is hypothesised that this observation relates to the increased midsole stiffness found in the cooled footwear condition. Sinclair, Taylor, and Hobbs (2013b) showed that rearfoot eversion was a significant regulator of impact loading during running. Therefore, it can be speculated that runners utilised this mechanism as a way of attenuating some of the increased load experienced by the musculoskeletal system when wearing the cooled footwear. A further explanation is that the reduction in midsole deformation in the cooled condition. As runners land on the lateral aspect of the foot, this may have facilitated a longer moment arm and thus creating greater peak eversion angle. Nonetheless, this observation may also be clinically relevant as increased ankle eversion and internal tibial rotation have been implicated in the aetiology of a number of chronic running injuries such as plantar fasciitis, tibial stress syndrome, patellofemoral pain and illiotibial band syndrome (Duffey et al., 2000; Lee, Hertel, & Lee, 2010; Willems et al., 2006).

A limitation of the current study is that the footwear were cooled artificially using a freezer rather than naturally using the environmental temperature. However, the midsole temperature and shoe deformation measurements obtained from the current study correspond well with those shown by Kinoshita and Bates (1996), who used an environmental chamber to simulate spring and winter temperatures. This indicates that the temperature differences between footwear closely resemble those that might be observed naturally with different environmental ambient temperatures. A further potential limitation is the

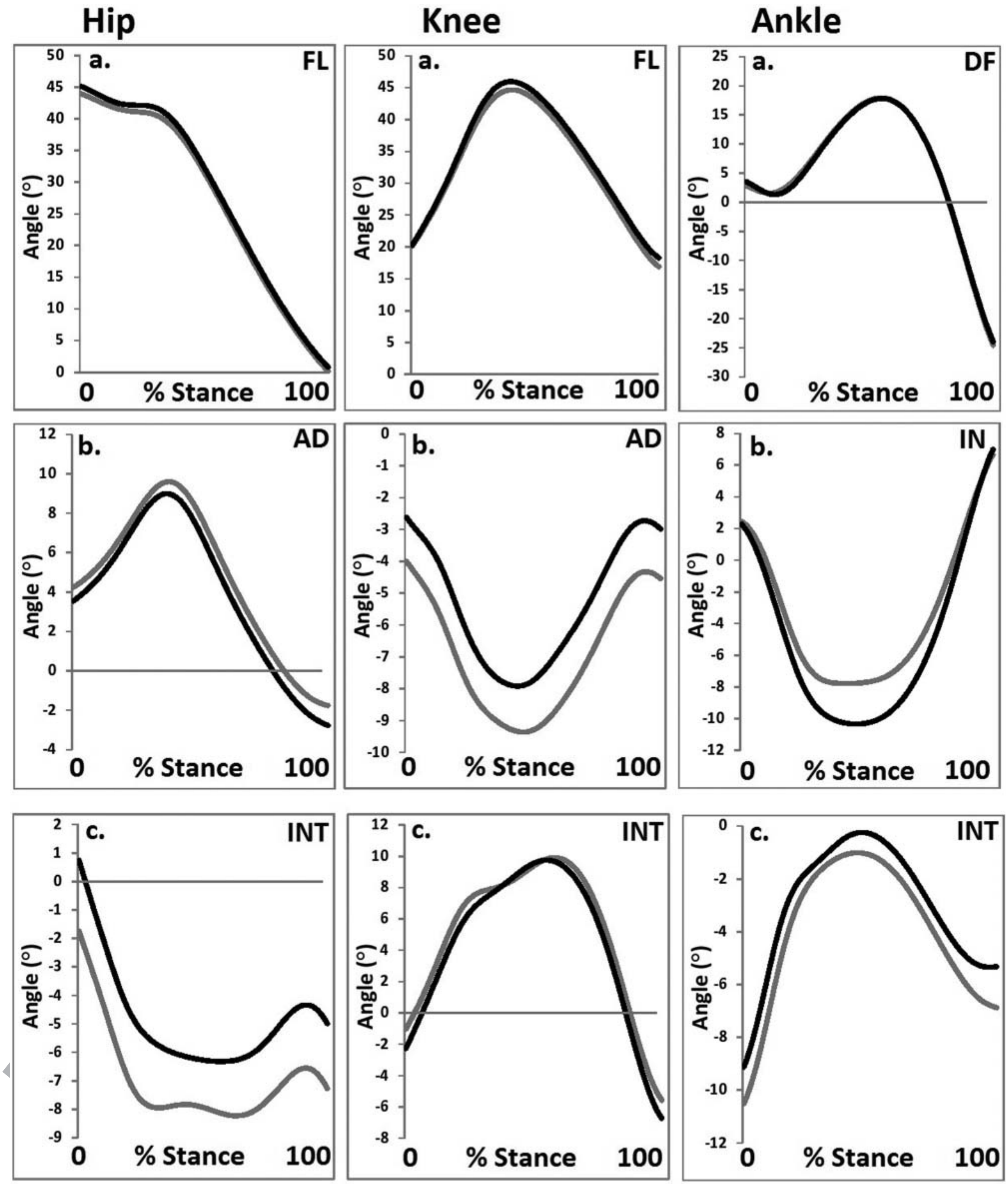

Figure 2. Hip knee and ankle joint kinematics in the (a) sagittal, (b) coronal and (c) transverse planes as a function of footwear temperature (black = cooled, grey = normal), (FL = flexion, AD = adduction, IN = inversion, INT = internal).

mechanism utilised to measure midsole deformation using a marker positioned at the top of the shoe midsole. Whilst this technique did allow a repeatable method of quantifying midsole deformation in the current investigation, it may have led to an underestimation of midsole deformation. Future work should seek to examine the effects of footwear temperature on midsole deformation using a more appropriately positioned marker.

Table 5. Tibial internal rotation parameters as a function of footwear temperature.

	Normal		Cooled		
	Mean	SD	Mean	SD	
Transverse plane					
Angle at footstrike (°)	0.47	5.86	0.97	6.00	
Angle at toe-off (°)	−0.20	6.23	−0.59	6.78	
Peak internal rotation (°)	7.77	4.87	10.67	5.79	*
Range of motion (°)	2.86	1.82	2.59	1.79	
Relative range of motion (°)	7.29	3.46	9.70	2.29	
EV/TIR ratio	2.18	1.25	1.71	0.84	

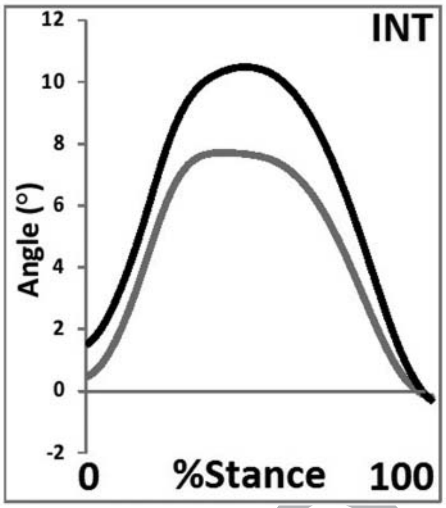

Figure 3. Tibial internal rotation as a function of footwear temperature (black = cooled, grey = normal), (INT = internal).

In conclusion, although previous analyses have investigated the effects of footwear temperature, this has only involved *in vitro* mechanical testing. The current investigation addresses this by providing a comparison of the kinetics and kinematics of running when running in cooled and normal temperature footwear. The current study shows that impact loading and peak eversion/tibial internal rotation parameters were significantly greater when running in cooled footwear. First, these observations provide further insight into the mechanical alterations that runners make when the temperature of their footwear is reduced. In addition, this study indicates that running in cooled footwear may place runners at increased risk from the biomechanical parameters linked to the aetiology of injuries.

Q8

Disclosure statement

No potential conflict of interest was reported by the authors.

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